Flavor Violation Tests of Warped/Composite SM in the Two-Site Approach Part I

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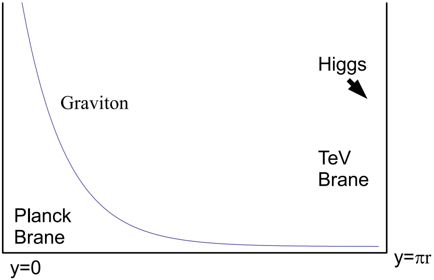
Outline

RS models

- Geometrical solution to the Planck -Electroweak hierarchy problem (Randall,Sundrum 99)

$$(ds)^2 = e^{-2ky} dx^\mu dx_\mu + (dy)^2 \qquad (0 \leq y \leq \pi r_c) \tag{1}$$

- $$\frac{< v >}{M_{Pl}} \sim e^{-k\pi r_c} \tag{2}$$

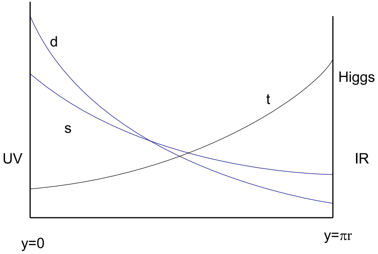


Fermions in the bulk

One can easily explain large hierarchies in the fermion masses by putting them in the bulk. The mass will be proportional to the overlap integral between the fermion profiles and Higgs field.

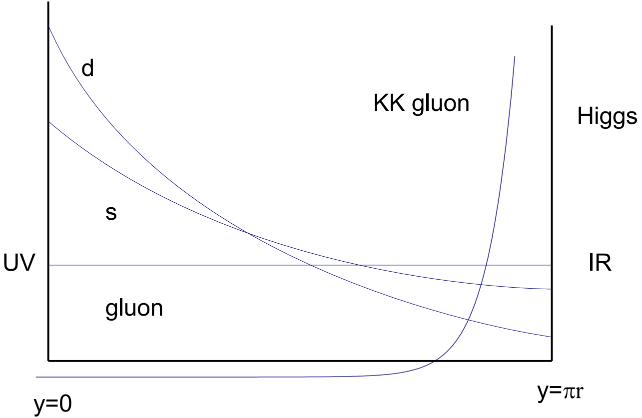
$$f(y) \propto e^{-cky} \quad (3)$$

Small variation in the 5D mass parameter c will lead to the large hierarchies in the fermion masses.

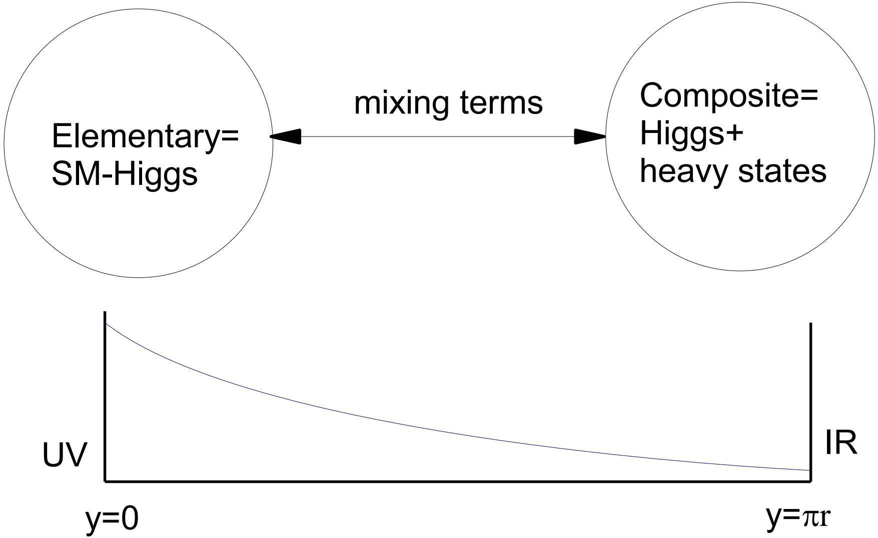


RS GIM

large flavor violating operators will be suppressed



- We want to study the phenomenology of the RS models, assuming that all the hierarchies in the fermion masses and mixings are generated by the warp factors, and all the Yukawa couplings are of the same order i.e. "anarchical".
- Instead of using specific $5D$ model we will use more economical description, namely "two site model"(Contino,Sundrum,Kramer,Son, 06), which is 4D effective field theory obtained by truncating RS model to the SM particles and their first KK excitations.
- Based on the AdS/CFT correspondence applied to a slice of AdS, the two-site model describes two sectors: composites of purely $4D$ strong dynamics and elementary fields (which are not part of the strong dynamics). These two sectors mix, with the resulting mass eigenstates being the SM particles and heavier partners, which correspond to the zero and KK modes of the $5D$ model.


Elementary=
SM-Higgs
mixing terms
Composite=
Higgs+
heavy states
UV
IR
y=0
y=πr

Elementary sector

- Gauge Fields $SU(3) \otimes SU(2)_L \otimes U(1)_Y$

$$A_\mu \equiv \{G_\mu, W_\mu, B_\mu\} \tag{4}$$

- fermion electroweak doublets,

$$\psi_L \equiv \{q_{Li} = (u_{Li}, d_{Li}), l_{Li} = (\nu_{Li}, e_{Li})\} \tag{5}$$

- singlets,

$$\tilde{\psi}_R \equiv \{u_{Ri}, d_{Ri}, \nu_{Ri}, e_{Ri}\}. \tag{6}$$

- Interactions

$$\mathcal{L}^{\text{elementary}} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}_L i D \psi_L + \bar{\tilde{\psi}}_R i D \tilde{\psi}_R. \tag{7}$$

Composite Sector

$SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- 15 heavy vector mesons

$$\rho^*_\mu = \{G^*_\mu, W^*_\mu, \mathcal{B}^*_\mu\}\,, \qquad \tilde{\rho}_\mu = \left\{\tilde{W}^\pm_\mu \equiv \frac{\tilde{W}_1 \mp i\,\tilde{W}_2}{\sqrt{2}}, \tilde{\mathcal{B}}_\mu\right\}. \qquad (8)$$

- $SU(2)_L$ doublets :

$$\chi \equiv (Q_i = \{U_i, D_i\}, L_i = \{N_i, E_i\}) \qquad (9)$$

and $SU(2)_L$ singlets:

$$\tilde{\chi} = \left(\tilde{U}_i, \tilde{D}_i, \tilde{E}_i, \tilde{N}_i\right) \qquad (10)$$

- Higgs field $SU(2)_L \otimes SU(2)_R$: $(H, \tilde{H})$
- Interactions

$$\mathcal{L}_{\text{composite}} = -\frac{1}{4}\rho^2_{\mu\nu} + \frac{M^2_*}{2}\rho^2_\mu + |D_\mu H|^2 - V(H) +$$
$$+\bar{\chi}(iD - m_*)\chi + \bar{\tilde{\chi}}(iD - \tilde{m}_*)\tilde{\chi} - \bar{\chi}(Y^u_*\tilde{H}\tilde{\chi}^u + Y^d_* H\tilde{\chi}^d) + h.c. \quad (11)$$

Mixing between composite and elementary sectors

The two sectors (composite and elementary) are connected to each other by the mixing terms

$$\mathcal{L}_{\text{mixing}} = -M_*^2 \frac{g_{el}}{g_*} A_\mu \rho_\mu^* + \frac{M_*^2}{2} \left(\frac{g_{el}}{g_*} A_\mu \right)^2 + (\bar{\psi}_L \Delta \chi_R + \bar{\tilde{\psi}}_R \tilde{\Delta} \tilde{\chi}_L + \text{h.c.}). \tag{12}$$

The elementary and composite mass eigenstates could be redefined by new mass eigenstates

$$\begin{pmatrix} A_\mu \\ \rho^*_\mu \end{pmatrix} \to \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu \\ \rho^*_\mu \end{pmatrix}, \qquad \tan\theta = \frac{g_{el}}{g_*}, \tag{13}$$

$$\begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix} \to \begin{pmatrix} \cos\varphi_{\psi_L} & -\sin\varphi_{\psi_L} \\ \sin\varphi_{\psi_L} & \cos\varphi_{\psi_L} \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix}, \qquad \tan\varphi_{\psi_L} = \frac{\Delta}{m_*}, \tag{14}$$

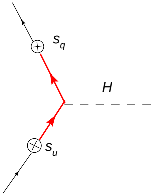
$$\begin{pmatrix} \tilde\psi_R \\ \tilde\chi_R \end{pmatrix} \to \begin{pmatrix} \cos\varphi_{\tilde\psi_R} & -\sin\varphi_{\tilde\psi_R} \\ \sin\varphi_{\tilde\psi_R} & \cos\varphi_{\tilde\psi_R} \end{pmatrix} \begin{pmatrix} \tilde\psi_R \\ \tilde\chi_R \end{pmatrix}, \qquad \tan\varphi_{\tilde\psi_R} = \frac{\tilde\Delta}{\tilde m_*}. \tag{15}$$

Where $(A_\mu, \psi_L, \tilde\psi_R)$ are SM fields, which are massless before EWSB, and $(\rho^\mu_*, \chi_L, \tilde\chi_R)$ are new heavy mass eigenstates prior to EWSB. To shorten our notations we will denote

$$\theta \equiv \theta_1, \theta_2, \theta_3, \quad \varphi_{\psi_L} \equiv \varphi_{q_{Li}}, \varphi_{l_{Li}}, \quad \varphi_{\tilde\psi_R} \equiv \varphi_{u_{Ri}}, \varphi_{d_{Ri}}, \varphi_{\nu_{Ri}}, \varphi_{e_{Ri}}$$
$$\tan\theta \equiv t, \quad \sin\varphi_{u^i_R} \equiv s_u, \quad \sin\varphi_{d^i_R} \equiv s_d, \quad \sin\varphi_{q_{Li}} \equiv s_q. \tag{16}$$

Anarchy condition in the Two-Site language

The mass of the SM fermions in the Two Site model will be



$$= \frac{Y_* v}{\sqrt{2}} s_q s_u$$

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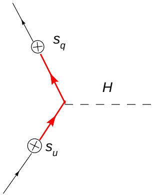

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Two-Site mimics RS model $\Longrightarrow$

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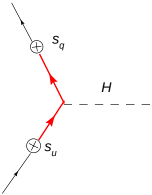
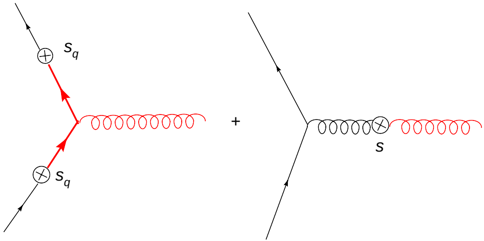


$$= \frac{Y_* v}{\sqrt{2}} s_q s_u$$

Two-Site mimics RS model $\Longrightarrow$ All the hierarchies in the SM fermion sector should be explained by the hierarchies of the mixing parameters $s_{q,u,d}$ and all the Yukawa couplings are of the same order -"Anarchical"

Interaction with vector bosons



$$
\begin{aligned}
&= \rho^*_\mu g \left(-c_q^2 \tan\theta + s_q^2 \frac{1}{\tan\theta} \right), \\
&g = g_* \sin\theta
\end{aligned}
\tag{17}
$$

Interactions with the Higgs and heavy vector bosons:

$$
\begin{aligned}
\mathcal{L}_Y = \quad & -Y_{*u}\tilde{H}s_q s_u \bar{q}_L u_R - Y_{*d}Hs_q s_d \bar{q}_L d_R \\
& -Y_{*u}\tilde{H}\left[c_q s_u \bar{Q}_L u_R + s_q c_u \bar{q}_L \tilde{U}_R\right] - Y_{*d}H\left[c_q s_d \bar{Q}_L d_R + s_q c_d \bar{q}_L \tilde{D}_R\right] \\
& -Y_{*u}\tilde{H}\left[c_q c_u \bar{Q}_L \tilde{U}_R + \bar{Q}_R \tilde{U}_L\right] - Y_{*d}H\left[c_q c_d \bar{Q}_L \tilde{D}_R + \bar{Q}_R \tilde{D}_L\right] \qquad (18)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L} \quad & = \rho^*_\mu g\left[\bar{q}_L\gamma_\mu q_L(-c_q^2 t + s_q^2\frac{1}{t})\right] + \rho^*_\mu g\left[(\bar{q}_L\gamma_\mu Q_L + \bar{Q}_L\gamma_\mu q_L)(s_q c_q(1+\frac{1}{t}))\right] \\
& +\rho^*_\mu g\left[\bar{Q}_L\gamma_\mu Q_L(c_q^2\frac{1}{t} - s_q^2 t)\right] \qquad (19)
\end{aligned}
$$

Two Site -Bulk Higgs correspondence

- $$\Psi(x,z) = \sum_n \psi^{(n)}(x)\chi_n(c,z) \tag{20}$$

- Zero mode profile

$$\begin{aligned} \chi_0(c,z) &= f(c)\left(\frac{z}{z_h}\right)^{2-c}\frac{1}{\sqrt{z_h}}\left(\frac{z_h}{z_v}\right)^{1/2-c} \\ f(c) &= \sqrt{\frac{1-2c}{1-(z_v/z_h)^{2c-1}}} \end{aligned} \tag{21}$$

- KK profile

$$\chi_n(c,z) = \left(\frac{z}{z_h}\right)^{5/2}\frac{1}{N_n^{\chi}\sqrt{\pi r_c}}[J_\alpha(m_n z) + b_\alpha(m_n)Y_\alpha(m_n z)] \tag{22}$$

$$\int_{z_h}^{z_v} dz(\frac{z_h}{z})^4\chi_n^2(c,z) = 1 \tag{23}$$

Similarly we can make decomposition of the Higgs and the vector field

$$\mathcal{A}_\mu(x,z) = \sum_n A^{(n)}(x) f_n(z) \tag{24}$$

$$\mathcal{H}(x,z) = v(\beta,z) + \sum_n H^{(n)}(x)\phi_n(z) \tag{25}$$

(Cacciapaglia,Csaki,Marandella,Terning 06)

$$\begin{aligned} v(\beta,z) &= v_4 z_v \sqrt{\frac{2(1+\beta)}{z_h^3(1-(z_h/z_v)^{2+2\beta})}} \left(\frac{z}{z_v}\right)^{2+\beta} \\ \beta &= \sqrt{4+\mu^2} \end{aligned} \tag{26}$$

Couplings between zero mode fermions and KK gluon are given by:

$$\sim g\left(-\frac{1}{\sqrt{k\pi r}} + f(c)^2\sqrt{k\pi r}\right), \quad g = \frac{g_{5D}}{\sqrt{\pi r}} \tag{27}$$

comparing it to the "Two-Site"

$$g\left(-\tan\theta + s^2\frac{1}{\tan\theta}\right), \quad g = \frac{g_*}{\sin\theta} \tag{28}$$

$$\begin{aligned} s_{L,R} \quad &\leftrightarrow \quad f_{L,R} && (29)\\ \frac{1}{k\pi r_c} \quad &\leftrightarrow \quad \tan^2\theta \\ g_* \quad &\leftrightarrow \quad g_5\sqrt{k} && (30) \end{aligned}$$

The couplings between fermions and Higgs are given by the overlap integrals

- $$\begin{aligned} Y_0\left(c_L, c_R, \beta\right) &= Y_5^{bulk} \int dz \left(\frac{z_h}{z}\right)^5 v(\beta, z)\chi_{0L}(c_L, z)\chi_{0R}(c_R, z)/v_4 \\ Y_{KK}\left(c_L, c_R, \beta\right) &= Y_5^{bulk} \int dz \left(\frac{z_h}{z}\right)^5 v(\beta, z)\chi_{nL}(c_L, z)\chi_{mR}(c_R, z)/v_4 \end{aligned}$$

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- $$\left.\frac{\chi_0(c, z)}{\chi_n(c, z)}\right|_{z=z_v} \propto f(c)$$
  $$Y_0\left(c_L, c_R, \beta\right) \sim Y_{KK} f(c_L) f(c_R) \tag{31}$$

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- comparing to the “Two Site”

$$Y_* \Longleftrightarrow Y_{KK} \tag{32}$$

- $$a(\beta, c_L, c_R) = \frac{Y_0\,(c_L, c_R, \beta)}{Y_{KK}\,f(c_L) f(c_R)}$$

β	0	1	2	∞
a	1.5	1	0.75	0.5

- $$a(\beta, c_L, c_R) = \frac{Y_0\left(c_L, c_R, \beta\right)}{Y_{KK} f(c_L) f(c_R)}$$

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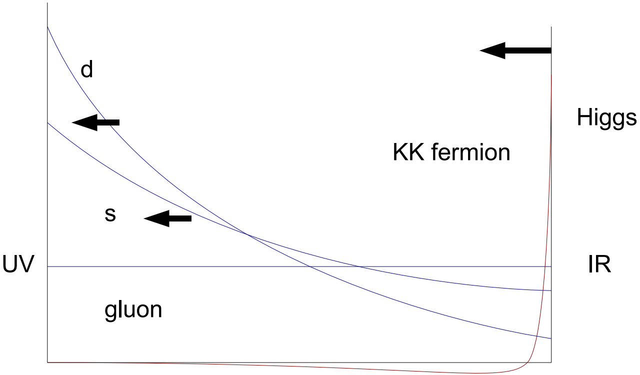

"Brane Higgs"

$$
\begin{aligned}
Y_0^{brane} &= \left(Y_5^{brane} k\right) f_L f_R \\
Y_{KK}^{brane} &= \left(2 Y_5^{brane} k\right) \\
a = \tfrac{1}{2} & \quad \beta = \infty
\end{aligned}
\tag{33}
$$

“Two Site”

$$
\begin{aligned}
Y_{SM} &= Y^* s_l s_r \quad Y_{\text{Heavy}} = Y^* c_l c_r \\
a_{\text{2-site}} &\approx 1
\end{aligned} \tag{34}
$$

correponds to $\beta = 1$ case with the bulk Higgs.

Summary

- “Two Site”' model captures robust features of the RS model, using fewer parameters
- Corresponds to the Bulk Higgs scenario
- “Two Site”-RS matching

$$\begin{aligned} s_{L,R} &\leftrightarrow f_{L,R} \qquad (35) \\ \frac{1}{k\pi r_c} &\leftrightarrow \tan^2\theta \\ g_* &\leftrightarrow g_5\sqrt{k} \\ Y_* &\leftrightarrow Y_{KK} \\ \text{SM states} &\leftrightarrow \text{zero modes} \\ \text{heavy states} &\leftrightarrow \text{KK modes} \end{aligned} \qquad (36)$$